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DMIC review OF RECENT DEVELOPMENTS

Aluminum and Magnesium

J. B. Hallowell • May 1, 1970

LANDING-GEAR CYLINDER BACK EXTRUDED

Variations in manufacturing processes to achieve improved stress-corrosion resistance in forged 7079 aluminum landing-gear cylinders have been examined at Wyman-Gordon.(1) Landing-gear cylinders are internally pressurized and are thus in tension throughout the barrel section. These cylinders have been produced in recent years from high-strength aluminum-zinc-magnesium type alloys, which are particularly susceptible to rapid stress-corrosion cracking at areas where "end-grain" is exposed, i.e., where the grain-flow direction is perpendicular to the final surface. The forging of cylinders is complicated by the need for a boss on one side of the cylinder. The variations in forging procedures used in this program are indicated in the sketch in Figure 1. All variations included an upset operation to produce the end region. The conventional production procedure (I) involved the forging of a symmetrical blank, the boss of which was formed by radial flow of metal in the final die-forging operation. Other variations in forging procedures aimed at achieving an improved grain-flow pattern on the inner surface of the barrel under the center boss included (II) the use of an oversize cylindrical section at the boss so that the boss was formed by machining, (III) forging of an assymmetric blank, or (IV) simply extruding and machining. Procedure V was the most successful in producing the desired flow pattern. In this procedure, an upset blank was held in press dies and pierced by a side ram, which produced back extrusion of the cylindrical section over the ram (initial flow), followed by reverse motion due to the stepped ram to force the metal into the shape of the boss. With this latter procedure, grain-flow patterns in the boss were parallel to the finished part surface. Both variations in the extrusion procedures also were found to produce an ideal circumferential flow at the bore. Furthermore, the extrusions showed no flash-line end-grain. All production procedures produced tensile properties satisfying the requirements of AMS 4138. The principal differences found in the various products were in stress-corrosion properties, selected results for which are given in Table 1, and in costs as indicated in Table 2. Both procedures by virtue of grain-flow patterns produced the desired superiority in corrosion resistance, not only under the critical center boss, but also throughout the entire cylinder bore. The back extrusion was evaluated as being the least expensive of the procedures.

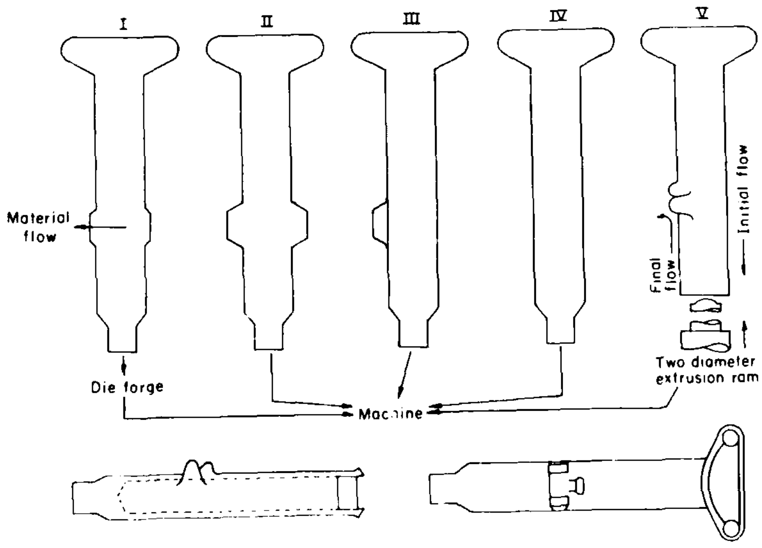

FIGURE 1. DIAGRAM OF ALTERNATIVE FABRICATION PROCEDURES(1)

TABLE 1. SELECTED STRESS-CORROSION DATA FOR 7079 ALLOY CYLINDERS FORMED BY VARIOUS PROCEDURES(1)

(3.5% NaCl Alternate Immersion at 75 to 80 F)

Forging Procedure	Location	Stress, ksi	Failure Time, days
I	Under center boss	30	14,15,28,>30,>30
II			12,12,12,>30,>30
III			12,12,1[illegible],16,30
IV			All >30
V			44,>90,>90,>90,>90
I	Barrel section	30	11,10,30
II			7,7,12
III			10,12,9
IV			>30,>30,>30
V			>90,>90,>90,>90

TABLE 2. ESTIMATED RELATIVE COSTS OF PRODUCTS PRODUCED BY VARIOUS PROCEDURES(1)

Procedure	Relative Cost Ratios (100-part basis)
I	1.00
II	0.98
III	0.97
IV	2.21
V	0.82

PRESSURE VESSELS FABRICATED BY EB WELDING OF 2219 ALLOY

The fabrication of spherical pressure vessels by electron-beam welding of 2219-T6E46 alloy has been studied at Boeing. In this study, electron-beam welding was found to be superior to TIG welding on the basis of higher properties and reliability.[2] The variables studied included heat treating welding sequences, material thickness, welding speeds and power input, beam focus, and porosity effects. The properties for constant-thickness materials in the various weld conditions are compared in Table 3. Here, the superiority of electron-beam to TIG welding is apparent in that the as-welded tensile strength is roughly 20 percent higher and fracture toughness is also higher. The data also indicate the feasibility of postweld aging of the electron-beam-welded material without the drastic loss of ductility found in TIG-welded joints owing to more extensive thermal effects in the wider heat-affected zone. A study of weld-repair techniques showed that the best results were obtained with full-penetration rewelding, with some reduction in the as-repaired-weld properties, as listed in the table. The study also established a relationship between pore size and location and fatigue strength of the welded joints. Four pressure vessels were fabricated on a simulated production basis and were found to fully support the feasibility of electron-beam welding for pressure-vessel applications.

TABLE 3. EFFECTS OF PROCESSING VARIATIONS ON PROPERTIES OF WELDED 1/2-INCH-THICK 2219 ALLOY(2)

(Electron-Beam Welded at 90 ipm, 23.5 kv, 370 ma.)

Condition	Test Temp, F	Ultimate Tensile Strength,(a) ksi	Tensile Yield Strength, ksi	Elongation, percent	Fracture Toughness,(b) ksi$\sqrt{in.}$
2219-T6E46 (base metal)	RT	64.3	45.6	18	42.7
TIG-welded (as welded)	RT	41.0	21.1	8	24.2(c)-35.2(d)
T6E46, EB welded	RT	50.1	37.1	13	37.7(c)
	-320	68.8	44.7	14.5	37.1(d)
T42, EB welded, then aged to T6E46	RT	56.6	49.5	10.5	37.8(c)
	-320	73.0	54.5	13.5	--
EB welded, then solution treated and aged to T6E46	RT	66.1	48.9	16	40.1(c)
	-320	76.6	53.9	15.5	--
Reweld repair	RT	41.8	24.3	6	--

(a) Failure location not defined.
(b) Tested at -320 F.
(c) Weld center flaw.
(d) Fusion line flaw.

EFFECTS OF COMPOSITION AND HEAT TREATMENT ON STRENGTH AND CORROSION RESISTANCE

In a program at Alcoa Research Laboratories, the effects of variations in zinc, copper, chromium, manganese, silver, and zirconium content and heat-treating procedures on the strength, corrosion-resistance, and heat-treating behavior of 7075-type alloys have been studied.[3] The variations in composition studied are indicated in Table 4. All material was 2-inch-thick plate to allow conclusions to be applied to heavy-section parts. The study included extensive investigation of the effects of variations and combinations of aging times and temperature, isothermal and step-aging treatments, and quenching and heating rates on tensile stress-corrosion properties. All of the experimental alloys were as strong or stronger than the 7075 base-line composition; the highest strengths were found in the chromium-free (X7375 type) alloys. Silver additions were found to increase strength only in alloys without chromium in the cold-water spray-quenched condition, principally in the overaged condition. Another conclusion drawn was that the substitution of either zirconium or manganese for chromium in 7075 decreased the quench sensitivity of these alloys so that the strengths of the chromium-free alloys after a boiling water quench were higher than those of the standard 7075 composition. Silver additions increased the quench sensitivity of all of the alloys except the one containing zirconium.

TABLE 4. VARIATIONS IN COMPOSITION OF EXPERIMENTAL ALLOYS(3)

Alloy	Composition, percent						
	Zn	Mg	Cu	Cr	Zr	Mn	Ag
7075	5.8	2.3	1.5	0.2	--	--	--
7075 + Ag	5.9	2.4	1.5	0.2	--	--	0.37
Hi-Zn 7075	6.6	2.2	1.4	0.2	--	--	--
Hi-Zn 7075 + Ag	6.6	2.3	1.4	0.2	--	--	0.39
Hi-Cu 7075	5.5	2.3	2.4	0.2	--	--	--
Hi-Zn 7075	8.2	2.4	1.7	0.2	--	--	--
X7375(a) + Zr	5.8	2.3	1.3	--	0.12	--	--
X7375 + Zr + Ag	5.8	2.5	1.5	--	0.14	--	0.35
X7375 + Mn	5.7	2.4	1.5	--	--	0.34	--
X7375 + Mn + Ag	5.7	2.5	1.5	--	--	0.34	0.38

(a) X7375 denotes 7075 composition without chromium.

The effects of silver on final aged strength were studied extensively, particularly as applied to quenching rate and rate of heating to aging temperature. The principal mechanism by which silver imparts higher properties was identified, and correlated with final properties, as its interaction with heating rate to aging temperature. This is illustrated by the curve in Figure 2. The conclusion is that silver-bearing alloys show a relative superiority to silver-

free 7075 only when high heating rates are used, as in laboratory studies using small specimens. This relative superiority is due only to the decrease in the properties of the standard 7075 alloy as heating rate is increased. There is little difference in properties when silver-free and silver-containing 7075-type alloys are heated at rates typical of those used for heating heavy sections in production-type furnaces. The superiority of the 7075 + Ag alloy at high heating rates is attributed to the presence of precipitate nuclei formed by silver-vacancy interactions. Such nuclei are initially absent in silver-free 7075 alloy but apparently form during a slow heating to the aging temperature.

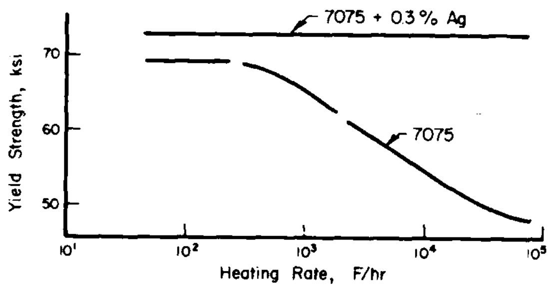

FIGURE 2. COMPARISON OF TRANSVERSE YIELD STRENGTH OF TWO ALLOYS AS A FUNCTION OF HEATING RATE TO THE AGING TEMPERATURE(3)

(Solution Heat Treated, Cold-Water Quenched, Aged 8 Hours at 315 F.)

The results of stress-corrosion-cracking tests showed no special benefits of the various compositional variations in the study except for increases in either zinc or copper additions. Increases in either of these additions increased by 3 to 8 ksi the strength level at which good resistance to stress-corrosion cracking existed.

In a subsequent program at Alcoa, investigations were continued on high-strength, corrosion-resistant alloys containing increased amounts of copper in the form of heavy plate.(4) The most attractive combinations of properties were obtained in the composition ranges of 5.8 to 6.3 percent zinc 2.0 to 2.5 percent magnesium, 2.1 to 2.6 percent copper, and 0.09 to 0.15 percent zirconium with iron and silicon limited to 0.12 percent maximum and 0.10 percent maximum, respectively. The strength levels achieved in the experimental alloys are indicated by the selected data given in Table 5, where the alloys are listed in order of decreasing strength for the given aging condition. The conclusions drawn from this study include the observation that increasing amounts of solute increase aged tensile strengths. Furthermore, the alloys with higher copper content were found to show higher strengths with increasing times and temperatures of solution heat treatment, which were associated with decreased amounts of Al_2CuMg phase in the structure and higher elongations in the short-transverse direction. Other conclusions drawn from this study are illustrated in Figure 3. Here, short-transverse yield strengths of 2-inch-thick plate of three experimental alloys are compared with typical properties of three standard materials as a function of quenching rate. The experimental alloys show good retention of strength at low quenching rates and yield strengths higher than those of the standard materials. Although atmospheric stress-corrosion-cracking tests are not yet complete, the threshold stress for stress-corrosion cracking is estimated as 25 ksi for the experimental alloys.

TABLE 5. LONG TRANSVERSE TENSILE YIELD STRENGTHS OF EXPERIMENTAL ALLOYS(4)

(2-Inch-Thick Plate, Solution Heat Treated, Aged 24 Hours at 250 F and 2 Hours at 350 F.)

Alloy No.	Composition, percent Zn	Mg	Cu	Other	Tensile Yield Strength, ksi
[illegible]	7.1	2.2	2.6	0.35 Mn	83.5
10	7.0	2.4	2.3	0.11 Zr	83
7	6.7	2.4	2.4	0.13 Mn, 0.10 Zr	81.5
6	6.3	2.1	2.2	0.11 Zr	81
4	[illegible]	[illegible]	2.5	0.11 Zr	78
9	6.8	2.0	2.1	0.54 [illegible]	78
8	6.3	2.1	2.3	0.17 Mn	77
3	5.8	2.4	2.4	0.30 Mn	77
7175	5.9	2.5	1.4	0.2 Cr	69

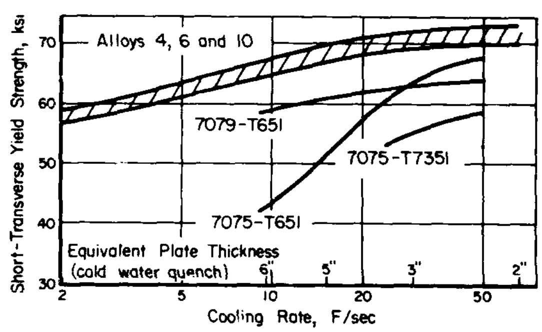

FIGURE 3. COMPARISON OF STRENGTH AND QUENCH SENSITIVITY OF EXPERIMENTAL AND PRODUCTION ALLOYS(4)

(See Table 9 for composition of alloys.)

CHARACTERISTICS OF X7080, 7178, AND 7075 ALLOYS

A recent study performed at Alcoa Research Laboratories has included extensive testing to compare the properties of two thicknesses (1/2 and 1-3/8 inch) of plate and two forms (11/16-inch-thick integrally stiffened panel and 3-1/2 x 7-1/2-inch bar) of extrusions.(5) The combinations of forms, alloys, and tempers included plate of X7080-T7E41 and 7178-T651, and extrusions of 7075-T6510, 7075-T73510, X7080-T7E42, and 7178-T6510. The results of this and prior programs allow the comparison of the properties of a number of alloys in currently used tempers. Selected data for 1-3/8-inch-thick plate collected by the authors are given in Table 6, with materials listed in order of decreasing tensile strength. The tensile properties of the four types of integrally stiffened extrusions examined are given in Table 7, which also shows the small variations in properties from location to location. The investigators also advanced a proposed method of correlating the results for smooth stress-corrosion specimens with those obtained for fracture-toughness-type specimens exposed to corrosive (NaCl solution) environments.

TABLE 6. COMPARISON OF TENSILE PROPERTIES IN 1-3/8-INCH-THICK ROLLED PLATE(5)

Alloy and Temper	Longitudinal TS, ksi	Longitudinal TYS, ksi	Longitudinal Elong, %	Long Transverse TS, ksi	Long Transverse TYS, ksi	Long Transverse Elong, %	Short Transverse TS, ksi	Short Transverse TYS, ksi	Short Transverse Elong, %
7178-T651	92.5	81.9	9.0	87.8	77.8	9.0	80.2	68.1	2.2
7075-T651	86.7	78.4	11.2	85.1	76.1	11.3	80.5	67.2	3.4
7079-T651	83.0	76.3	11.2	82.8	73.2	11.2	78.4	68.0	4.6
2020-T651	82.0	76.6	6.0	82.3	77.8	2.3	76.6	74.0	0.8
7001-T75	81.0	71.1	9.5	80.4	70.5	8.8	73.0	66.3	1.9
7075-T7351	72.4	61.2	12.3	71.1	60.0	11.1	69.2	58.3	5.2
2024-T8[illegible]	71.9	65.8	8.1	71.0	65.0	7.[illegible]	67.7	63.2	2.0
X7080-T7E41	67.[illegible]	50.2	14.[illegible]	[illegible].3	59.6	12.5	67.1	56.3	7.0
2219-T851	66.6	51.2	10.5	65.8	50.4	10.4	66.7	51.5	6.1

TABLE 7. COMPARISON OF TENSILE PROPERTIES IN INTEGRALLY STIFFENED EXTRUSIONS(4)

Material	Edge TS, ksi	Edge TYS, ksi	Edge Elongation, %	Center TS, ksi	Center TYS, ksi	Center Elongation, %
7075-T6510	88.2	80.6	13.0	90.9	81.7	12.0
7075-T73510	73.3	63.0	14.5	72.5	62.1	13.5
X7080-T7E42	69.2	60.9	16.0	68.5	61.0	17.0
7178-T6510	91.2	85.1	11.5	93.4	86.4	10.0

EVALUATION OF 7049-T73 ALUMINUM

A new Kaiser aluminum alloy is now being evaluated.(6,7,8) The composition of the alloy, known as 7049-T73, is given in Table 8. Alloy 7049-T73 is proposed as an alloy equal in strength to 7079-T6 and 7075-T6, but possessing superior stress-corrosion-cracking resistance. Further, the alloy is intended for use in forgings with section thicknesses up to 5 inches. Proposed minimum tensile properties are given in Table 9. Stress-corrosion-cracking resistance is quoted in terms of no evidence of cracking after 30 days' exposure in 3-1/2 NaCl alternate immersion at room temperature when stressed at 75 percent of the yield strength.

AGING OF MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

The aging of magnesium-lithium-aluminum alloys of the LA141 type was studied at Lockheed/Sunnyvale.(9) The variables studied included lithium, aluminum, and oxygen contents and aging temperatures of -3 to 120 F. Age hardening was found to be limited to alloys with less than 15 wt% lithium (with 1 wt% aluminum present) and to alloys with more than 0.5 wt% aluminum (with 14 wt% lithium present). For the analysis of the hardness data obtained from aging experiments, a technique was employed whereby the hardness data could be compared with those of aluminum alloys, for which various age-hardening mechanisms have been studied in detail. The hardness data are given in terms of plots of the function 1/1-f, where $f = R_t - R_i / R_f - R_i$ and R_t is the measured hardness, R_i is the hardness before aging, and R_f is the highest hardness obtained during the aging treatment. Thus, hardness is presented as the fraction of the change from initial to final hardnesses. This makes the kinetic curves of aging independent of absolute hardness level and allows comparison of curve shapes for different age-hardening systems. The various shapes of the aging curves are indicated in Figure 4. The authors conclude that the new linearity of the aging curve at 120 F indicates a single-stage precipitation reaction, whereas the increasing curvatures of the plots for aging at 75 and 32 F indicate less simple precipitation mechanisms. For the analysis, the aging curve shapes for the magnesium-lithium-aluminum alloys are matched with those for the aging of aluminum-copper alloys for which mechanisms have been identified in the following manner:

Mg-Li-Al Aging Temperature	Matching Al-Cu Aging Conditions: Alloy	Aging Temperature	Mechanism
-3 F	Al-4Cu	110 C (230 F)	GP[1] → GP[2]
32 F	Al-2.8Cu	110 C (230 F)	GP[1] → GP[2] + [illegible]
75 F	Al-2.5Cu	110 C (230 F)	GP[1] → "
120 F	Al-4.5Cu	220 C (428 F)	Single-step precipitation

TABLE 8. COMPOSITION LIMITS FOR 7049 ALLOY (WEIGHT PERCENT)

Element	Minimum	Maximum	Element	Minimum	Maximum
Zinc	7.2	8.2	Silicon	--	0.25
Magnesium	2.0	2.9	Iron	--	0.35
Copper	1.2	1.9	Other, each	--	0.05
Chromium	0.10	0.22	Other, total	--	0.15
Manganese	--	0.20	Aluminum	Balance	
Titanium	--	0.10			

TABLE 9. PROPOSED MINIMUM TENSILE PROPERTIES OF 7049-T73 ALLOY HAND FORGINGS

Heat-Treated Thickness, in.	Longitudinal UTS, ksi	Longitudinal TYS, ksi	Longitudinal Elong, %	Long Transverse UTS, ksi	Long Transverse TYS, ksi	Long Transverse Elong, %	Short Transverse UTS, ksi	Short Transverse TYS, ksi	Short Transverse Elong, %
2 to 3	71	61	9	71	59	4	69	58	3
3 to 4	69	59	8	69	57	3	67	56	3
4 to 5	67	56	7	67	56	3	66	55	2

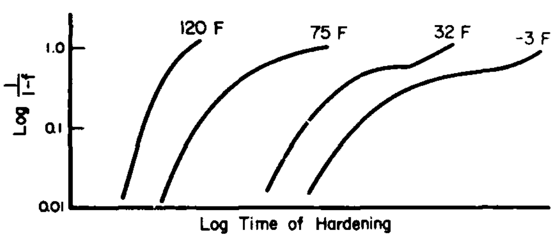

FIGURE 4. COMPARISON OF SHAPES AND AGE-HARDENING CURVES FOR Mg-Li-Al ALLOYS(9)

The rate of formation of AlLi compound was studied by solution heat treating, aging at temperatures of 200 to 310 F, and following the subsequent room-temperature aging behavior. The study implied that the greater the hardness increase at room temperature, the less the precipitation of AlLi during the aging treatment. Using, again, an expression of fractional degree of precipitation based on maximum initial (artificially aged) hardness and minimum stable hardness values, the rates of AlLi formation in various alloys were determined. The rates of formation of AlLi in experimental alloys were found to be 30 to 40 times as rapid as in commercially produced alloys. The rapid formation of AlLi compound in the experimental alloys was attributed to heterogeneous nucleation by oxide particles as a consequence of their higher oxygen content, which varied from 0.11 to 0.60 percent.

The commercial alloys contained generally lower oxygen contents of <0.015 to 0.12 percent.

Mg-Li ALLOY HONEYCOMB CORE

The feasibility of producing lightweight expanded honeycomb core from a magnesium-lithium alloy was studied at Battelle.(10) The program was aimed at exploiting the high-modulus-to-density ratio, 114 x 10^6 inches, of the magnesium-lithium alloys. A core density of about 1.7 lb/ft^3 is possible using these materials. The alloy used, designated as LAZ933, had the nominal composition Mg-9Li-3Al-3Zn. Alloy strips 1 inch wide were cold rolled from 0.010 inch thick to 0.0015 inch thick and laid up alternately with transverse, properly spaced, 0.009-inch-wide strips of adhesive. The layup was then bonded by preheating at 200 F for 1 hour to dry the assembly, and then by heating to 335 to 340 F and applying pressure to produce an adhesive bond thickness of 0.002 inch. The bonded assembly was then expanded to obtain a honeycomb panel having 1/4-inch hexagonal cells. The variables studied included the effect of cleaning and coating procedures on bond strength. All material was cleaned using a ferric nitrate bright pickle. Because of the desireability of protecting LAZ933 alloy from oxidation during storage, the effects of a prebonding coating of an electrolytic Dow 17 anodize on bond strength were determined. The effect of the anodize on lap-shear strength of adhesive-bonded joints is shown in Figure 5, for a range of test temperatures. The target bond strength in this program was 1500 psi over the entire temperature range, and was achieved with the uncoated material. The coating reduced the joint strength and was identified as the source of failure. However, one of the recommendations coming from this program is the development of a mechanically strong and adherent protective coating which could be applied after the manufacture of the honeycomb core to extend its storage life prior to applying face sheets.

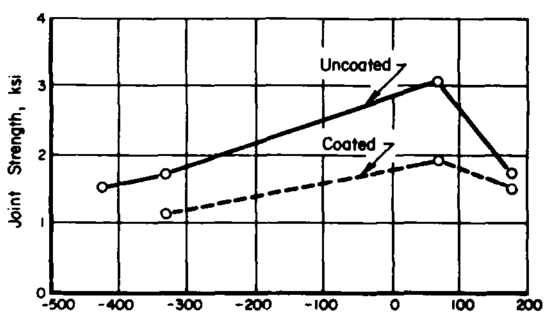

FIGURE 5. EFFECT OF COATING TREATMENT ON JOINT STRENGTH OF ADHESIVE-BONDED LAZ933 ALLOY(10)

PROGRAMS IN PROGRESS

North American Rockwell is currently conducting a study for the Naval Air Systems Command on the improvement of strength and corrosion resistance of 7075 alloy by thermal-mechanical treatments.(11) The program includes the low-temperature, liquid nitrogen, room-temperature, or warm (325 to 350 F) working of various tempers of 7075 alloy and evaluation of the properties obtained.

Two programs are currently being sponsored by the Air Force Systems Command with the aims of obtaining: (1) a yield strength of 72 ksi in 3-inch-thick plate, (2) a yield strength of 63 ksi in 8-inch-thick forgings, (3) a short-transverse stress-corrosion threshold stress of 25 ksi, (4) a minimum fracture toughness of 33 ksi$\sqrt{in.}$, and (5) a fatigue strength equal to that of 7075 alloy.(12,13) In both programs, alloys are being studied containing nominally 6 to 7 percent zinc and 2.3 to 2.5 percent magnesium, with various single or combined additions of up to 0.3 percent vanadium, zirconium, manganese, chromium, iron, or nickel. In one program, alloys with 2.3 percent copper are being used; the other, alloys with 1.2 percent copper. Alloys studied in these programs have exhibited the target properties of strength and fracture toughness, but the evaluations of corrosion resistance and fatigue properties remain to be completed before final conclusions may be drawn.

The Navy-sponsored program at Alcoa on the development of a high-strength stress-corrosion resistant naval aircraft alloy has been extended, and the properties of an alloy designated as MA15 (Al-6.25Zn-2.4Mg-2.25Cu-0.13Zn), in thicknesses up to 6 inches, is being studied.(14)

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